SOFTWARE FOR SIGNAL PROCESSING AND DISPLAY OF LARGE 3-D DATA SETS

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INTRODUCTION

We have recently developed a software system, called DETECT/NDE, which provides a powerful environment for processing and visualizing large ultrasonic data sets. This system runs on X-Windows UNIX workstations and on VAX/VMS computers, and combines interactive graphics-based visualization with signal processing algorithms. The two main features of this package are: (1) the interactive generation and display of B-scans and C-scans from the 3-D data sets; and (2) the provision of high resolution deconvolution and inversion procedures for improving the interpretability of the data. In addition, numerous other utilities allow image processing, animation and 3-D rendering of the data.

GENERAL FEATURES OF DETECT/NDE

DETECT/NDE is specifically designed for rapid visualization and display of large 3-D data sets. It also allows the display of 2-D images and individual traces derived from these data. Processing and display utilities are implemented in the form of a series of screens, each with display windows and annotated buttons. The functions of the package are invoked through a point-and-click interface, using a mouse to select options in the form of buttons on the screens. Each of these screens has an on-line Help function to provide immediate detailed information about the functionality of that screen.

This point-and-click interface is also used to provide easy file specification, as input and output files are selected from automatically displayed menus. A file naming convention has been implemented which defines the type and format of data stored. It also denotes the processing history for the data, using a series of standard suffixes.

The graphical interface for DETECT/NDE is written in IDL, an Interactive Data Language developed by Research Systems, Inc. The IDL code for DETECT/NDE is provided with the package, allowing for easy modification and customization of the software as new applications arise. A set of deconvolution and inversion techniques written in Fortran allows processing of the data to enhance its temporal resolution. This processing can significantly improve the detection of defects in the material under inspection. A simulation utility is also provided to allow simple forward modeling.

Except for the simulation and signal processing utilities of DETECT/NDE, all functions are run as foreground tasks. Data, once read into memory, may be passed between different program segments. For the signal processing functions, input and output always involve data files, with an option to visualize the processed data.

OVERALL STRUCTURE OF DETECT/NDE

DETECT/NDE consists of a number of subsystems, each of which performs specific types of processing or display.

The *Z-scan Subsystem* provides visual techniques to analyze an entire volume of 3-D ultrasonic data, termed a *Z-scan*, using C-scans, B-scans, and A-scans. The Z-scan Subsystem graphical interface provides control over processing parameters, such as trace start and end gates, amplitude or time of flight modes, time of flight threshold, and number of C-scan segments to produce. The interface also provides graphical controls to perform more detailed analysis of Z-scan data using A-scan, B-scan and C-scan visualization subsystems. This screen is illustrated and discussed in more detail below.

The *C-scan Subsystem* provides for the display and image processing of individual C-scans.

The *B-scan Subsystem* displays a B-scan image and an average A-scan derived from a specified number of traces in the B-scan. The interface also allows the analysis of the current average A-scan by invoking the A-scan subsystem.

The *A-scan Subsystem* displays a trace and its power spectrum. A wavelet may be selected from the trace, and the SNR may be estimated from the power spectrum. The interface also provides for joint time-frequency visualization of the trace using the Wigner distribution.

The *Wavelet Subsystem* displays a wavelet and its power spectrum, and allows the definition of a spectral region of high SNR.

The *Digital Signal Processing Subsystem* contains processing and resolution enhancement utilities of three basic types:

- Trace manipulations, including alignment, low-pass filtering, envelope computation and subtraction of a constant trace.
- Deconvolution processing to improve the time resolution of the data. Four techniques are available, namely Wiener deconvolution, autoregressive spectral extrapolation, L1 norm sparse deconvolution, and L2 norm sparse deconvolution. These techniques are described in more detail below.
- High resolution inversion processing to yield a structural model for the material. The procedure is described in more detail below.

These techniques may be applied to A-scans, B-scans or entire Z-scans. They operate on a single trace at a time.

The *Image Processing Subsystem* provides a variety of image processing functions which can be used to assist in the interpretation of ultrasonic images. These include median and boxcar filtering, edge enhancement, histogram display and equalization, image scaling and proportional display, visualization of the image as a surface, and image combination. The output of one image processing procedure may be used as input for another, allowing cascaded processing.

The *Simulation Subsystem* allows the generation of synthetic A-scans, B-scans or Z-scans. These are formed from the convolution of a wavelet with spike series arising from the type of forward model selected.

The *Conversion Subsystem* allows data files to be converted between various defined formats.

Z-SCAN VISUALIZATION

The Z-scan visualization screen is used to interactively process, display and interpret 3-D ultrasonic data. An example of the Z-scan visualization screen is shown in Figure 1. In this screen, the data are presented in five windows:

The upper left window (Figure 1a) shows one of a series of C-scan segments, each computed for a narrow time gate. The slider can be used to step rapidly through these C-scan segments and view the data within the various time gates.

The upper centre window (Figure 1b) shows an overall C-scan derived from the data using a broad time gate (which is specified in the A-scan or B-scan windows). The cross-hairs in the C-scan window control the display of B-scans in the x- and y-directions, and the display of a "live" A-scan at the point of intersection.

The upper right (Figure 1c) and lower centre (Figure 1d) windows show B-scans in the two dimensions, corresponding to the vertical and horizontal cursor lines in the broad gate C-scan image.

The lower right window (Figure 1e) shows the "live" A-scan at the point of intersection of the cursor lines in the overall C-scan window; as the lines are moved, the corresponding trace is dynamically displayed.

A status window provides notification about the current state of any ongoing computations or required actions. The buttons along the bottom of Figure 1 control the additional functionality of this screen. Functions may be invoked to compute amplitude or time-of-flight C-scans, modify time gates, change the color map, invoke image processing utilities, save or print the images, invoke the animation and slicer (3-D rendering) utilities and perform a variety of other operations. The conditions for generating the C-scan segments may be changed and the entire data set reprocessed to generate a new set of images; these manipulations, applied to a 16 Mbyte data set, required less than one minute on an IBM RS/6000 Model 550 workstation (rated at 25.6 Mflops).

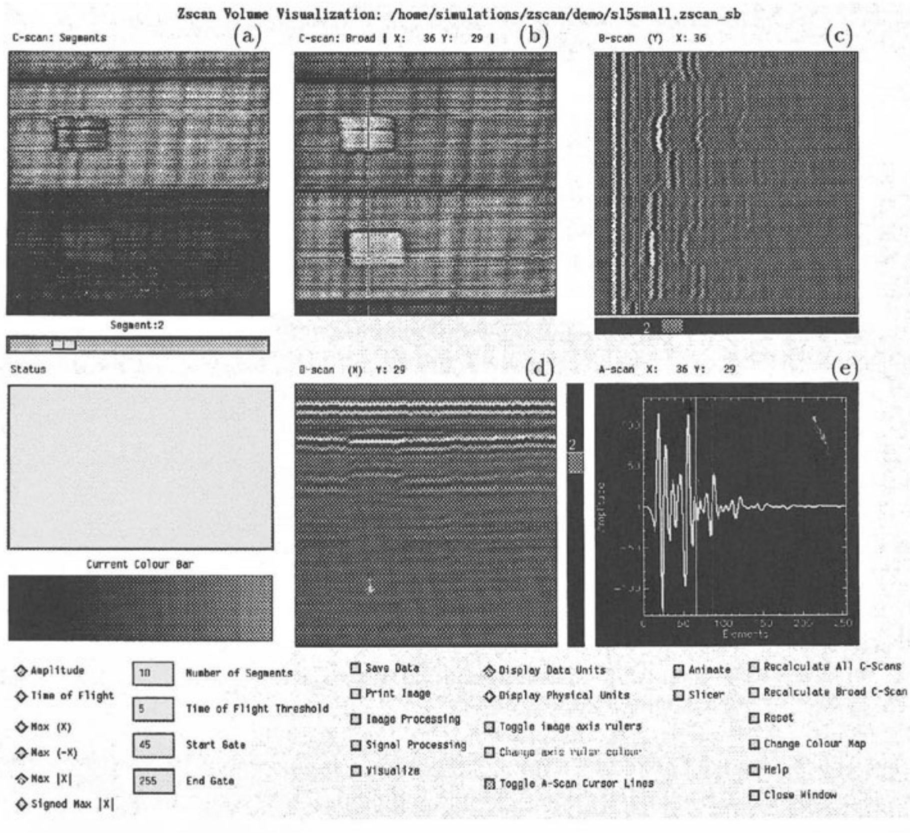


Figure 1. Example of Z-scan visualization screen.

The real ultrasonic data used to generate the images consisted of 256×256 traces, each with 256 elements, for a total of 16 Mbytes. They were obtained from a graphite-epoxy/titanium steplap joint specimen. Two simulated structural flaws were present in the material: these were rectangular Teflon inserts, folded to trap a thin layer of air, and simulate a disbond or delamination. The structure of this specimen is shown in Figure 2.

DIGITAL SIGNAL PROCESSING

The time resolution of the data can be improved by applying the DETECT/NDE deconvolution and inversion techniques to the individual traces of a B-scan or a Z-scan. Four deconvolution techniques and one inversion technique are available; these techniques require an estimate of the wavelet and the specification of certain parameters required by the particular technique. The procedures are described briefly below and their performance is illustrated in Figure 3. The original data for this example are shown in Figure 3a, and illustrate the spreading effect of the wavelet and the presence of multiple reflections.

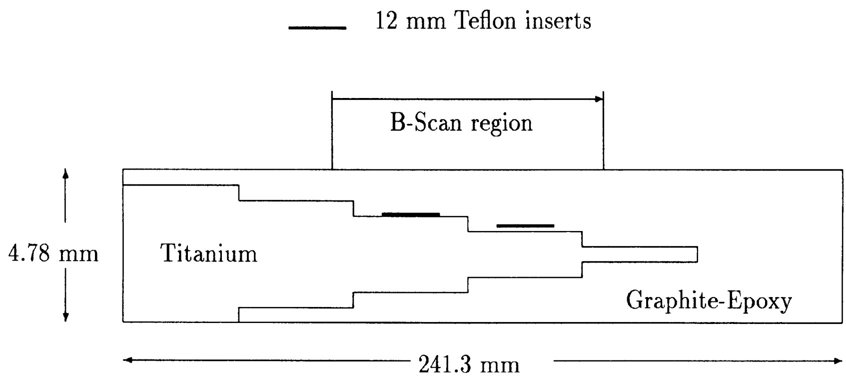


Figure 2. Structural model of specimen used for acquiring real data.

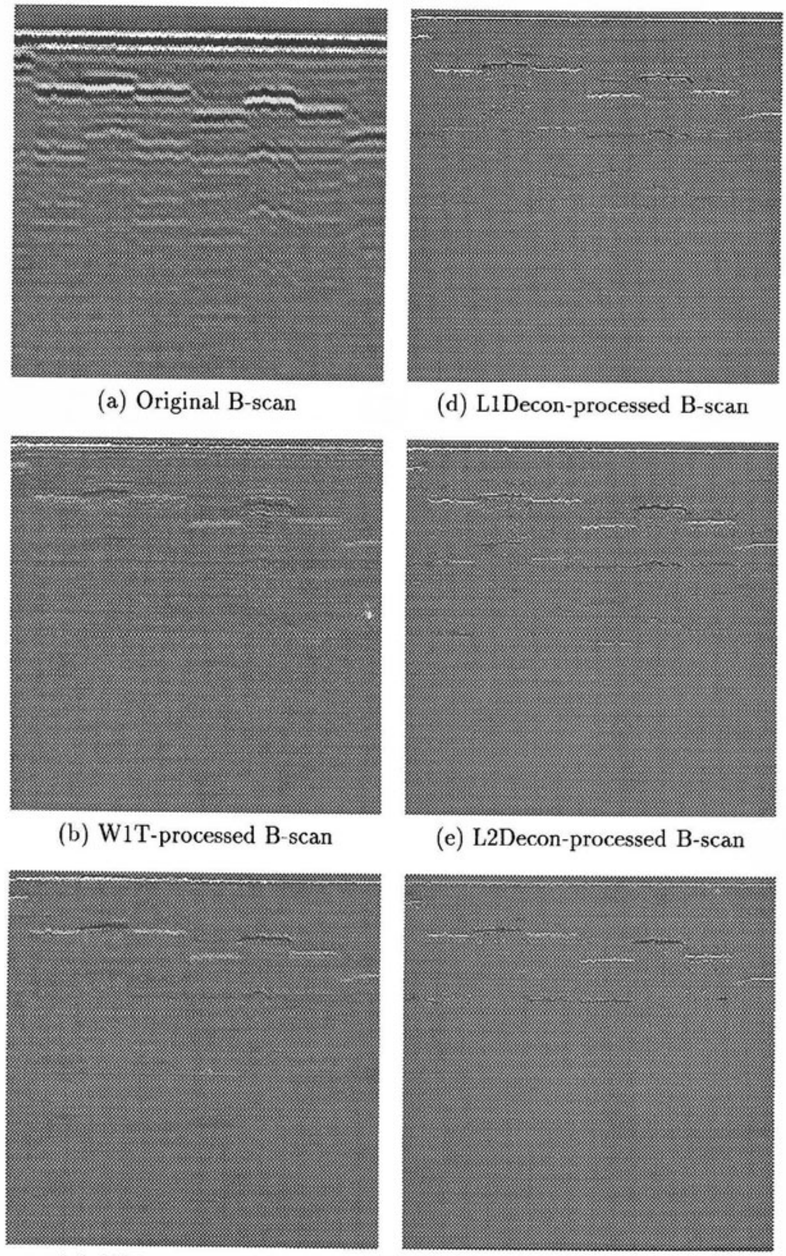
Wiener 1-D time domain deconvolution (W1T) is a standard procedure which involves inverse filtering of the data with a minimum variance filter of specified length. In the W1T-processed image (Figure 3b), the increase in resolution is apparent relative to the original data, but substantial sidelobes are present.

Autoregressive spectral extrapolation (ASE) [1] involves frequency domain deconvolution of the trace, followed by generation of an autoregressive filter within a frequency band of high SNR, using the Burg algorithm. This filter is then used to extrapolate the deconvolved transform throughout the entire spectrum. The extrapolated transform is then inverse transformed to yield the resolution-enhanced trace. The ASE-processed image (Figure 3c) shows a reduction in sidelobes relative to W1T, but the resolution of interfaces is somewhat uneven and decreases with time.

L1 norm sparse deconvolution (L1Decon) [2] extracts a sparse spike train from the trace using the L1 (least-absolute-values) norm. Spikes are extracted one-at-a-time in a locally optimal way until a sufficiently close fit to the trace is obtained or a specified maximum number of spikes is reached. It yields a sparse, highly accurate result, but is usually slower than other methods. The L1Decon-processed image (Figure 3d) shows a highly resolved estimate of the reflection series.

L2 norm sparse deconvolution (L2Decon) [3] also extracts a sparse spike train from the trace, but uses the L2 (least-squares) norm, and a different extraction strategy. It is the best overall deconvolution technique, yielding highly accurate sparse spike series in times comparable to those required by W1T and ASE. The L2Decon-processed image (Figure 3e) shows a highly resolved reflection series, very close to that produced by L1Decon, but obtained in one tenth of the time.

High resolution inversion (Invert) [3] estimates the layered structure for the material under inspection. It is a time domain approach which sequentially determines the positions and amplitudes of the reflection coefficients of the interfaces. It requires about the same time as L2Decon under typical conditions. In the Invert-processed image (Figure 3f), multiple reflections have been removed, and the first two interfaces have been clearly identified. In addition, the far titanium/graphite-epoxy interface has been detected in regions which are not under the defects. Inversion processing provides the clearest interpretation of the data.



(a) Original B-scan (d) L1Decon-processed B-scan

(b) W1T-processed B-scan (e) L2Decon-processed B-scan

(c) ASE-processed B-scan (f) Invert-processed B-scan

Figure 3. Comparison of performance of signal processing algorithms of DETECT/NDE.

CONCLUSIONS

The software system described in this paper provides a highly effective environment for the analysis and display of 3-D ultrasonic data sets. The choice of a UNIX workstation allows large data sets to be stored in memory and manipulated rapidly; for a 16-Mbyte data set, generation and display of new images after changing the processing conditions requires on the order of one minute on a 25.6-Mflop computer. Improved resolution of the positions and polarities of reflections within the data can be achieved through the use of the signal processing algorithms provided with the system. The overall software package is a powerful and flexible tool for visualization and interpretation of ultrasonic data.

ACKNOWLEDGEMENTS

The design of this software system was based on the results of research carried out during contracts with the Defence Research Establishment Pacific (DREP). We would like to thank Mr. Ken McRae of DREP for his valuable suggestions during the design of the visualization and processing functions, and Mr. Borna Noureddin of BCS for assistance in programming. The financial support of the Science Council of British Columbia in the form of a Technology B.C. grant is also acknowledged with thanks.

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